QUALIFICATION OF COMPONENTS FOR INSTALLATION IN LHC KICKER MAGNETS*

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Abstract

LHC injection kickers (MKI) are pulsed at high voltage to achieve magnetic field pulses with fast rise time. The MKIs contain a beam screen to help shield their ferrite yoke from beam induced heating. However, additional means of mitigating beam induced heating, for the high luminosity LHC (HL-LHC) era, are required. To achieve this, the MKIs are sequentially being upgraded to low impedance versions (MKI Cool) with several critical components including (a) a 3 m long alumina tube, installed in the magnet aperture, used to hold screen conductors that help shield the magnet yokes from beam induced heating; and (b) an RF damper which moves beam induced power from the ferrite yoke to a ferrite cylinder which is part of the damper. This paper discusses the measurements carried out to qualify these components for installation in an MKI Cool. In addition, for the alumina tube, the interpretation of the measurement data is discussed together with the optimisation of the angular orientation of the tube in the magnet aperture.

INTRODUCTION

The MKIs are kicker magnets used to inject particle beams into the Large Hadron Collider (LHC). Four MKIs are used to inject Beam 1 and four for injecting Beam 2 [1]. Each MKI magnet is housed in a vacuum tank, is ~3 m long and contains ferrite yokes that guide a pulsed magnetic field to deflect the injected particle beams. The ferrite yokes, which are situated close to the beam, result in high beam coupling impedance and, thus, significant beam induced heat deposition in the ferrites [2, 3]. If the ferrite yokes heat to the Curie temperature, they would lose their magnetic properties and the magnet would be temporarily unable to inject beam [4]. To reduce the beam coupling impedance of the MKIs, screen conductors are placed along the aperture and surrounding the beam: these carry the image current of the beam [5, 6]. The screen conductors are supported in slots in an alumina tube placed inside the magnet aperture. The first part of this paper presents the procedure for measuring and qualifying the alumina tubes.

To further reduce the beam-induced power deposition in the ferrite yoke, a so-called RF (Radio Frequency) damper has been placed at the input end of each MKI magnet. The RF damper consists of a ferrite cylinder that surrounds the alumina tube (Fig. 1), outside the magnet aperture, and captures a portion of the electromagnetic fields excited by the particle beam. This reduces the heating of the yokes, by moving a significant portion of the beam-induced power deposition to the RF damper [7]. With the high intensities expected in the HL-LHC era, and without extra cooling, the RF damper would heat up to the Curie temperature, losing its functionality [8]. To avoid such a scenario, the so-called MKI Cool incorporates a water circuit to cool the damper's ferrite (Fig. 1). The thermal contact between ferrite and the external copper cylinder plays a crucial role in achieving effective cooling: the second part of this paper presents the procedure for measuring the thermal contact of the RF dampers. Details of the manufacturing of the damper are presented in [9].

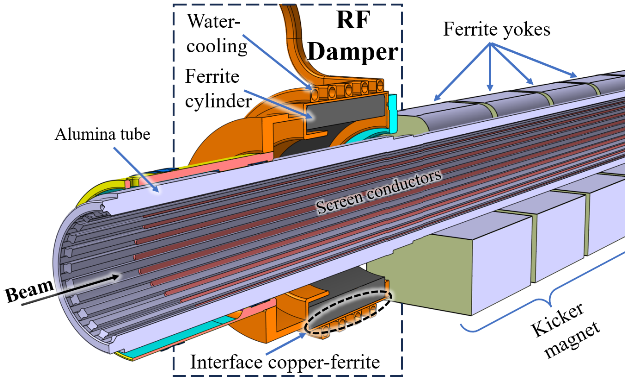

Figure 1: 3D model showing RF damper and alumina tube.

The MKIs are progressively being upgraded to the MKI Cool version [10] and all eight magnets plus the spares must be ready for the beginning of Hi-Lumi operation. New alumina tubes and water-cooled RF dampers are needed for these upgrades.

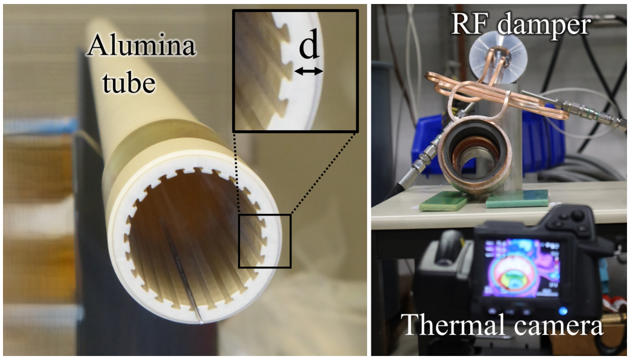

Figure 2: Alumina tube during thickness measurements (left) and RF damper during a test with thermal camera (right).

ALUMINA TUBE

Each MKI uses a ~3 m long alumina tube (Fig. 2), with 24 slots on its inner wall to hold the screen conductors. The tube has an inner diameter of approx. 42 mm, and an outer

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diameter of 51 mm over most of its length. The tube is manufactured by extrusion and during the process the tube may bend a little, such that the inner passage has a slight banana shape. After sintering, the outside of the tube is machined to ensure that it is straight and will fit into the 54 mm × 54 mm magnet aperture, with 1.5 mm clearance. However, the inside of the hole will keep its original, slight banana, trajectory, leading to non-uniform wall thickness along the length. The minimum acceptable wall thickness, adjacent to any screen conductor slot (d in Fig. 2), is 2 mm.

Recently, during high voltage (HV) pulse conditioning of an MKI, an alumina tube was punctured, rendering the tube unusable [11, 12]. The cause was the tube wall being too thin at the position where it was punctured: here the alumina could not sustain the HV (~25 kV) difference between the screen conductors (ground potential during the flattop of a pulse) and the HV busbar, which is pulsed at ~25 kV. To prevent this from happening again, a measurement technique has been developed to verify the tube minimum wall thickness and hence properly qualify the tube for installation.

In addition, the alumina tubes used in the MKI Cool magnets will be Cr_2O_3 coated, by Polyteknik [13], to mitigate electron cloud [14]. The tubes already installed in the MKI kickers do not have the coating and, although only very mildly radioactive, cannot readily be sent outside CERN for coating: hence new tubes must be procured, for the future MKI Cool magnets.

Electric Fields in The Magnet Aperture

The puncture of the alumina tube led to a detailed study of the electric fields that occur in the aperture of the MKI during the pulsing of the magnet, in particular during the flattop of the pulse, which is up to 8 µs duration [15]. During the pulse flattop, the ferrite and HV busbar (Fig. 3) are all at HV, whereas the screen conductors are at 0 V [5]. Thus, there is a high electric field between the screen conductors and the busbar/ferrite during the flattop: the electric field is dependent upon the wall thickness of the tube (d) and the location of the screen conductors in the aperture. Parametric electrostatic simulations, using Opera 2D, predict the maximum electric field at each angular position (θ), for a given wall thickness (d) of the tube [16]. As expected, a thinner tube wall results in a higher electric field. The predicted maximum field ($E_{\max}$) can be expressed as follows:

$$E_{\max} = f(\theta, d) \tag{1}$$

The U-shaped aperture results in the smallest gap, and hence the highest electric field, between the screen conductors and the HV regions at the bottom, left and right, as shown in Fig. 3. Hence, these are the critical positions, where sufficient alumina wall thickness is required. For this reason, and since the tube has rotational symmetry, it was decided to optimise the angular rotation for installation, in such a way to avoid the thinnest walls being located in these critical positions.

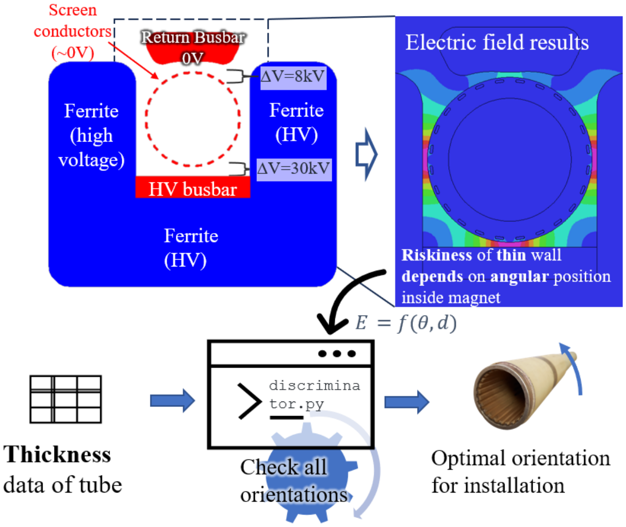

Figure 3: Schema representing the optimisation of the tube rotation. Colours represent the electric field magnitude.

Qualification Procedure

The qualification procedure of an alumina MKI tube consists of the following steps:

1. **Thickness measurement of the tube** [17]. The tube is held on two insulating supports, well away from metallic surfaces. The wall thickness of the alumina tube, beside a slot, is measured at eleven positions along the length and at 12 angular positions (one out of two slots), resulting in a table of 11×12=132 values. The measurement device, a Magna-Mike thickness gauge [18], uses the Hall Effect to measure the distance between a probe, which is placed touching the outside at the bottom of the tube, and a magnetic wire, that is positioned in the bottom slot. After each measurement the magnetic wire is displaced by pushing it to the next longitudinal position, until the entire length of the tube is measured. Once a slot is completed, the tube is rotated to the next slot of interest.
2. **Optimisation of the orientation of the tube** [19]. A Python script has been developed, that uses the relationship between, wall thickness and angular position, obtained from the Opera 2D simulations (Eq. 1). The thickness data, from the measurements, is passed through this script, to determine the orientation of the tube that minimises the absolute maximum electric field: in addition, plots show the resulting electric fields and wall thicknesses in the optimised orientation. The tube is then marked to indicate its orientation for installation in the MKI kicker magnet.
3. **Additional considerations for tubes with twist** [19]. Some alumina tubes have been found to have a small twist (30° maximum to date) of the inner profile along the length, which results in the screen conductor changing their angular position along the tube. In this situation, the optimised orientation must be verified, and the distribution of the screen conductors inside the slots

must be slightly rotated to compensate the influence of the twist upon the induced voltage.

RF DAMPER

The RF damper of the MKI Cool consists of a ferrite cylinder inserted in a copper sleeve with a helical copper pipe on the outside (Fig. 1). Water circulating through the pipe cools the ferrite, which heats due to absorbing the electromagnetic wakefields of the beam. To efficiently remove heat and keep the ferrite below 100°C [20], a minimum thermal contact conductance (TCC) of 1000 $W/(m^2 \cdot K)$ is required [20] between the ferrite and the copper sleeve.

Thermal Measurements on RF Dampers

Transient thermal measurements are required to determine the TCC of a damper [21]. A damper is placed in an oven and uniformly heated to ~80 °C. Then, it is taken out and connected to a water circuit. A thermal camera is set up to record the temperature on the inner surface of the ferrite every 14 s, approx. half-way along the length, at three different spots, each spot separated by an angle of ~40°. The water circuit is activated when the recording of the thermal camera starts. Each image records the temperature at the three spots: the rate of cooling of each spot is used to calculate a TCC of the interface between the ferrite and the copper sleeve [22].

Modelling of Thermal Circuit

To model the transient thermal behaviour of the damper, a detailed equivalent thermal circuit was used, where heat transfer is modelled as a current and temperature as a voltage [23]. In this equivalent circuit, the ferrite cylinder is modelled with ten 1 mm thick concentric cylinders to distribute heat capacity and thermal resistance throughout the volume. An additional resistor models the TCC of the interface between the ferrite and the sleeve. This transient model was run for a range of TCC values, to simulate transient thermal measurements, and the time constant of the temperature decrease of the inner ferrite was extracted, for each TCC value.

Finally, a simplified RC thermal equivalent circuit was built, where lumped ferrite thermal properties (thermal resistance and capacity) are modelled. To guarantee the equivalence between the simplified and the detailed model, a ”correction” factor is added to the resistor representing the thermal resistance of the ferrite cylinder, in the simple circuit. This factor is calculated such that the time constants of both the detailed and simplified circuits are identical for a specific TCC value. The time constant of this simplified RC circuit can be analytically computed, which results in an expression relating the time constant and the TCC of the interface between the ferrite and the copper.

Qualification Procedure

The qualification procedure [22] of an RF damper consists of the following steps:

1. **Transient cooling and thermal camera measurement**: repeated three times to cover the inner diameter of the ferrite.
2. **Extract the temperature values during cooling**, at the three spots per image.
3. **Fit each temperature curve to an exponential decay**, whose equation indicates the time constant. Figure 4 shows an example of measured temperatures and fitted curves.
4. **Calculate the TCC of the damper** from the analytical expression relating TCC to the time constant.

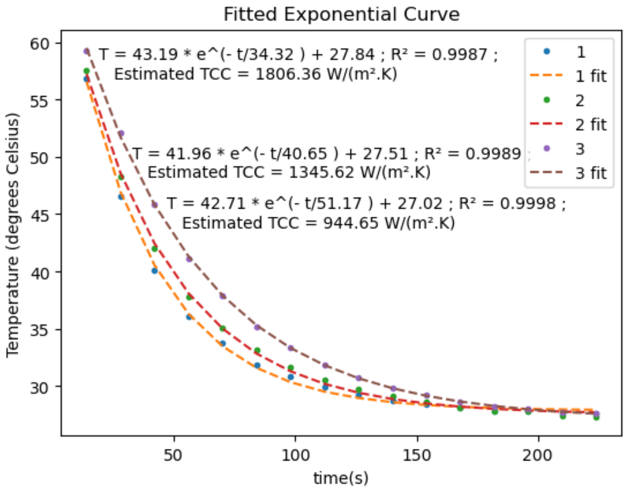

Figure 4: Measured temperature of 3-spots and fitted curves.

CONCLUSION

The wall thickness measurements of alumina tubes have been carried out to ensure a minimum of 2 mm. In addition, an optimisation of the rotational position is performed to ensure that the thinnest wall is not in the region with the highest electric field. The measurements provide repeatable and consistent results.

The RF damper qualification is crucial to guarantee an adequately high TCC between the ferrite cylinder and the copper sleeve. Otherwise, the ferrite cylinder could crack or reach its Curie temperature and become magnetically transparent, which in turn would significantly increase the beam induced power deposition in the yoke of the kicker magnet, potentially causing part of it to reach its Curie temperature and hence mis-kick injected beam.

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